THE HARVARD RADIO ASTRONOMY STATION AT FORT DAVIS, TEXAS

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Abstract: The Harvard Radio Astronomy Station at Fort Davis, Texas, came into operation in 1956 as a radio extension of the U.S. Air Force Sacramento Peak Observatory. The location near Fort Davis was chosen for the low level of man-made radio signals. Initially the receiving equipment at the site included a 28-ft diameter antenna and covered the range 100-580 MHz. The receivers swept through this band approximately three times per second, recording the spectrum of solar radio activity. In subsequent years the frequency range was extended to cover all or parts of 10 MHz to 4 GHz. All recorded solar bursts were identified according to five principal spectral types, and lists including times, durations, and frequency ranges of all solar activity were published. Studies of the bursts included analyses of their relationships to flares and other optical solar phenomena, and also their relationships to geophysical phenomena, including magnetic storms and polar blackouts. An 85-ft diameter antenna was installed in 1963, which during 1970-1974 was used for solar observations in the range 580 MHz to 4 GHz. Otherwise this antenna was used for non-solar radio astronomy, including lunar occultations of radio sources, measurements of flux densities at 5 GHz, investigations of the Galactic Center, and similar projects. The solar program was closed in late 1982 after 26 years of continuous operation. After 1974 the 85-ft antenna was used mainly in a program of VLBI network observations conducted by astronomers from Caltech and NRAO. In 1991 it was replaced by an antenna of the VLBA program of the NRAO. This paper describes some details of the antennas and receivers, and results of the solar studies. It also includes a brief discussion of the non-solar observations other than the VLBI program.

Keywords: Solar radio burst, radio spectra, sweep-frequency observations, solar burst classification, radio-quiet site, flare associations, geophysical associations.

1 REQUIREMENT FOR A SOLAR RADIO PROGRAM

By the mid-1950s it had become apparent that solar activity, which was well known in the optical spectrum from sunspots and solar flares, also included bursts of emission at radio frequencies. Australian observations (Wild and McCready, 1950) had shown that most of the more intense solar radio emissions could be observed at frequencies around one hundred mega-hertz. Also, it was known that measurement of the spectra of the bursts, i.e. the intensity of the emissions as functions of both frequency and time, allowed most of the bursts to be classified into several types, pre-sumably related to different mechanisms of generation. It was clearly important to extend solar observations in the U.S. to include the radio range, and thereby in-crease the fraction of time for which solar radio data were available. The planned International Geophysi-cal Year (IGY), 1957-1958, for which full 24-hour monitoring of the Sun was of basic importance for study of atmospheric and ionospheric phenomena, provided further impetus for the radio extension. It was therefore proposed to include the radio domain within the observations at the U.S. Air Force Solar Observatory at Sacramento Peak, New Mexico. The U.S. Air Force thus provided the initial funding for the project. Professor Donald H. Menzel of Harvard College Observatory, an authority on solar astronomy, played a leading role in the establishment of the solar radio project.

The specifications for the U.S. observing equipment, based on the astronomical requirements and the avail-able technology, resulted in the choice of a 28-ft (8.4-m) diameter parabolic antenna, equatorially mounted to track the Sun across the sky, with receiving equip-ment that would sweep through a range of 100 to approximately 600 MHz, several times each second.

2 CHOICE OF THE FORT DAVIS SITE

Dr Alan Maxwell, an experienced solar radio observer, was chosen to lead the U.S. radio project. In 1947-1948 he had made measurements of solar emission at 100 MHz in New Zealand as the subject for a Master's thesis (Orchiston, 2005, see Figure 8, p. 86) and then performed more extensive solar radio studies at the Jodrell Bank Radio Observatory of Manchester Uni-versity, U.K. From practical experience with solar observing at meter wavelengths, Maxwell had learned the importance of avoiding interference from trans-missions of services such as communication, broad-casting, etc. This was a particularly important consid-eration for the U.S. observations, which were intended to make measurements of the spectra of radio bursts over a wide frequency range. Thus Maxwell decided that locating the radio equipment in a sheltered valley would be much preferable to the mountaintop site of the observatory at Sacramento Peak. Henry Smith, a solar astronomer at Sacramento Peak, suggested to Maxwell that the ranching country near Fort Davis, in west Texas, would be a good area to investigate in his quest for a radio-quiet site. Marlyn Krebs, the Tech-nical Manager of the McDonald Observatory on Mt. Locke near Fort Davis, provided further help in locat-ing Cook Flat, a valley near the base of Mt. Locke just four miles from Fort Davis. This proved to be an excellent choice, and the Sproul family, whose ranch included a large part of Cook Flat, allowed Harvard University to lease a one-acre site for the solar radio observatory. The elevation of the site is 1600 m and the location is latitude 30° 38′ 08″ N., longitude 103° 56′ 42″ W. To reach the site from Fort Davis, take Highway 118 west which branches off about one mile north of the town center. Then after approximately four miles turn north on Sproul Road,[1] which is un-paved, and proceed for about 1.5 miles. The Harvard

site was on the left-hand side of the road, opposite the VLBA antenna (which was installed later—see Section 12, below).

3 OBSERVING INSTRUMENTATION

When Maxwell took up his position with Harvard College Observatory in 1955 orders had already been placed for a 28-ft. diameter equatorially-mounted antenna from D.S. Kennedy Co. of Cohasset, MA, a feed system covering 100-600 MHz from Jasik Labs. of Westbury, NY, and receivers from Airborne Instruments Laboratory Inc. (A.I.L.) of Mineola, NY. In 1956, Maxwell oversaw the erection of a small laboratory building at Cook Flat and the installation of the antenna and receiving system. Electric power was extended to the site and also an emergency motor generator was installed. A photograph of the station taken about 1958 is shown in Figure. 1. Space for offices and a photographic dark-room was rented in the Limpia Hotel building (which was not then in use as a hotel) in the Fort Davis town center. The program of routine observations of the Sun began the same year and was to run continuously through to 1982.

The initial frequency range was divided into three bands for efficient coverage by the antenna feeds. The feed design is described in detail by Jasik (1958), and consisted of a pair of half-wave dipoles for the 100-180 MHz band, a single dipole with a corner reflector for 180-320 MHz, and a horn for 320-580 MHz. The three feeds were ingeniously designed as a single structure with a common electrical center.[2] In each band a single linear polarization was received. For meridian pointing the polarization of the mid-frequency band was horizontal. Polarization of the two outer bands was orthogonal to that of the mid-frequency one, to minimize cross coupling. Receivers for the three bands were mechanically tunable using rotating capacitors driven at 200 rpm by electric motors. Thus the receivers swept in synchronism across each band approximately three times per second, as described by Goodman and Lebenbaum (1958). There were three rotating capacitors in each receiver, one each for the two amplifier stages and one for the local oscillator. The amplifiers used Western Electric (WE) 416B coaxial-type triodes in grounded-grid configuration.

The receiver outputs were displayed on three cathode ray tubes and continuously recorded on 35-mm film. The cathode ray tubes each had a vertical trace that swept downward as the associated receiver swept from the low to the high end of its range. The intensities of the traces were modulated in proportion

Figure 1: The 28-ft. diameter antenna and solar laboratory building as they appeared in 1958. The small antenna near the center of the picture, consisting of two dipoles with reflectors, was used with a 70 MHz fixed-frequency receiver and chart recorder. It provided a real-time indication of the state of solar activity, which was useful since the outputs of the spectral receivers could not be examined until the film was developed. Note that the dome of the McDonald Observatory, approximately 4 miles distant, is just visible on the horizon near the right-hand edge of the picture (Photograph supplied by A. Maxwell, Harvard College Observatory).

to the signal strengths from the receivers. The three display tubes were mounted with vertical alignment of the traces, and facing into a light-proof enclosure. A camera in which the film moved continuously in a horizontal direction recorded the three traces. As a result, the film showed three bands with time varying horizontally along the length of the film, and frequency running from 100 MHz at the top edge to 580 MHz at the bottom. Time marks were inserted at one minute intervals and frequency calibration signals every 20 min. Intensity calibration using a noise source was performed every three days when the 35-mm film was changed. Each evening after sunset the antenna was moved to the sunrise position and the whole system set to start automatically at sunrise. Further general descriptions of the instrumentation are given by Maxwell (1958), Maxwell et al. (1958), Thompson (1959b), and Maxwell (1971). Examples of the records and descriptions of the types of bursts observed are given in Section 5.

4 PROJECT STAFF IN THE EARLY YEARS

In addition to Alan Maxwell, the staff at the observatory during the first year included Govind Swarup and Samuel J. Goldstein Jr. (see Figure 2). Swarup left the Fort Davis project in late 1957 and went to Stanford University where he worked on the solar cross as a graduate student of R.N. Bracewell. He later returned to India where he had a distinguished career in radio astronomy, and was responsible for the conception and construction of two major instruments (Swarup 2006). Goldstein was interested in the angular sizes of solar bursts and built a two-element interferometer at the Fort Davis station. This instrument used two rhombic antennas 1 km apart on an east-west line, and a broadband receiver that covered approximately 105-140 MHz. Measurements on Type I and Type III bursts were made (Goldstein, 1959). Use of the interferometer was discontinued after Goldstein left for Stanford in 1958 where he too was a Ph.D. student of R.N. Bracewell. He later joined the Astronomy Department at the University of Virginia.

In August 1957, I (Dick Thompson) joined Maxwell's group. Like Maxwell, I had obtained a Ph.D. in radio astronomy from the University of Manchester. I remained with the project until November 1962 when I also joined the Radio Astronomy Institute at Stanford, and subsequently moved to the NRAO. Michael P. Hughes, a mathematician and very capable radio engineer, also from the U.K., joined the group in 1960. He moved to Stanford in 1966 to take a Ph.D. and subsequently had a teaching career at the West Kent College of Technology, U.K. Some of the staff and friends of the Fort Davis project are shown in Figure 3.

5 CLASSIFICATION OF SOLAR BURSTS

Most of the solar bursts in the meter- and decimeter-wavelength range can be classified as one of five types. Originally, Types I, II, and III were defined by Wild and McCready (1950), Type IV by Boischot (1957), and Type V by Wild et al. (1958). Although the great majority of bursts are classified within these types, other spectral details are sometimes seen: see e.g. Boischot et al. (1960). Examples of bursts from the Fort Davis records are shown in Figures 4-7, and include the extended frequency ranges described in
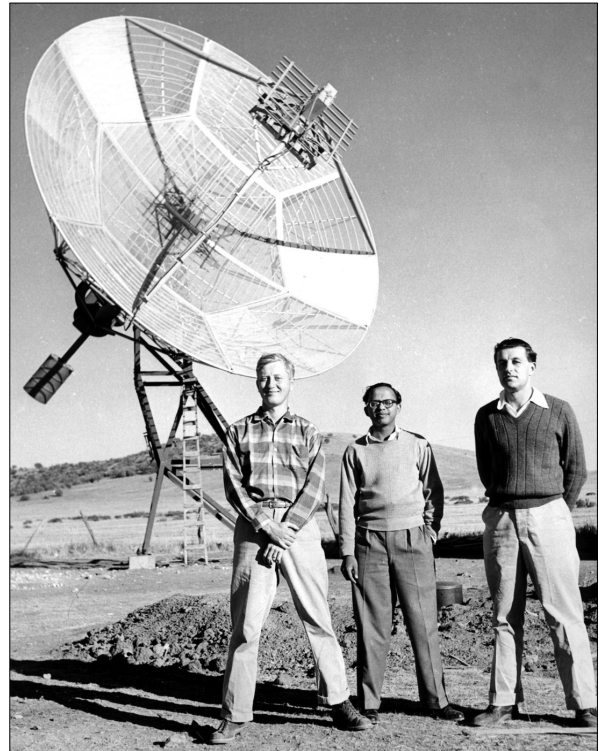

Figure 2: An early picture (1956) showing the three pioneers of the Fort Davis radio astronomy project (left to right): Sam Goldstein, Govind Swarup, and Alan Maxwell (Photograph supplied by A. Maxwell, Harvard College Observatory).

Sections 6 and 7. The five different spectral types are described below.

5.1 Type I, Noise Storm

A long series of short bursts which may continue for hours or days. These generally occur at frequencies below 200 MHz, and are superimposed upon a slowly-varying background enhancement. Individual bursts may have durations of less than one second, and often occur in clusters extending for many seconds. They are generated within the corona above active sunspot regions.

Figure 3: A farewell gathering in the solar laboratory on 26 October 1962, just prior to my leaving the project (left to right): myself; Mike Hughes; lab. assistant Charlie Murray; Bob Sproul, on whose ranch the site is located; Donald McIvor, a rancher who also had land in Cook Flat; and an unidentified person. Donald's mother was a member of the Locke family, who provided the site on Mt. Locke for the McDonald Observatory (Photograph supplied by A. Maxwell, Harvard College Observatory).
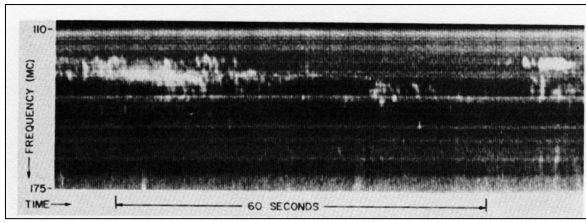
Figure 4: An example of noise storm (Type I) bursts. The enlargement is greater than in the next three figures to show the short duration of the individual bursts. The fine vertical structure extending across the frequency band is caused by the cathode-ray traces (after Maxwell, Swarup and Thompson, 1960).

5.2 Type II, Slow Drift Bursts

Strong bursts lasting for several minutes, usually starting in the frequency range 200-700 MHz and drifting down to less than 100 MHz. Frequency structure in the form of a fundamental and second harmonic is usually present. Type II bursts are attributed to fast-mode MHD (magneto-hydrodynamic) shock fronts moving outward through levels of decreasing plasma frequency within the corona.

5.3 Type III, Fast Drift Bursts

Relatively common bursts that start at frequencies of a few hundred MHz. Burst lifetimes are a few seconds, within which the maximum intensity drifts rapidly downward in frequency. They often occur in clusters that last for a few minutes. A type of fast-drift burst, in which the spectrum initially drifts downward in frequency and then turns upward again, was discovered at Fort Davis by Swarup. These appear on the Fort Davis records as an inverted letter U, and are known as
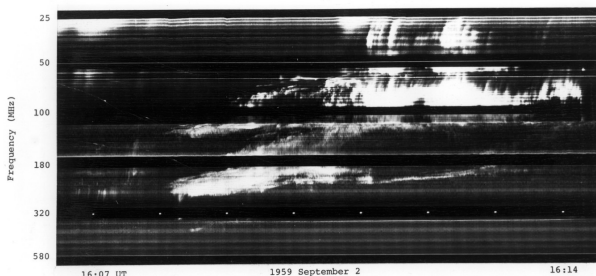

Figure 5: A Type II burst showing fundamental and harmonic frequency components. The white dots near the 320 MHz frequency level are one-minute time marks. Type III bursts can be seen between 16:11 and 16:13 UT in the 25-110 MHz range (Figure supplied by A. Maxwell, Harvard College Observatory).
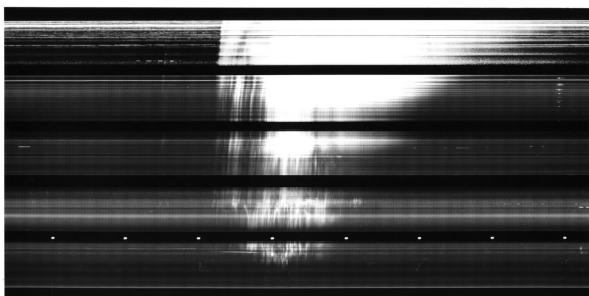

Figure 6: A group of Type III bursts accompanied by Type V continuum. The frequency range is 25-580 MHz as in Figure 4, and the time marks run from 19:25 to 19:32 UT on 4 February 1960 (Figure supplied by A. Maxwell, Harvard College Observatory).

'U-bursts' (Maxwell and Swarup 1958). U-bursts are believed to be generated by excitations that begin to move outward through the solar corona, but are guided by loops in the solar magnetic fields causing them to turn and move down toward the solar surface. They occur much less frequently than the usual Type III bursts.

5.4 Type IV, Continuum Emission

These appear as strong continuum emission with mainly smooth spectral features, but sometimes showing pulsations. They typically extend from a few hundred MHz to a few GHz and may last for several hours. They are usually associated with major outbursts on the Sun, and at their start are often accompanied by a Type II burst.

5.5 Type V

A short continuum burst, with duration increasing with decreasing frequency up to about 10 min, and usually accompanying T ype III bursts. Type IV and V emissions are attributed to the gyro-synchrotron mechanism.

5.6 The Fort Davis Observations

Each film record from the Fort Davis station was carefully analyzed, and the times and frequency ranges of all bursts were listed, along with their classification (as given above). Intensities were classified on a scale of one to three as described in Thompson (1961a). Summaries of these data were sent to the Sacramento Peak Solar Observatory and the National Oceanic and Atmospheric Administration (NOAA), and were published in the CRPL[3] (Boulder) Series F, Part B, *Monthly Bulletin of Solar-Geophysical Data*, and in the *IAU Quarterly Bulletin of Solar Activity*. Also, detailed information on radio emissions from specific solar flares was provided to a large number of individual investigators. The solar program covered the period October 1956 to October 1982, or approximately two cycles of the sunspot number activity, as shown in Figure 8.

6 FURTHER DETAILS OF THE SOLAR   INSTRUMENTATION

When I joined the Fort Davis group in 1957, my first important task was to replace the couplings in the drive shafts of the capacitors on the three sweep-frequency receivers. These had become worn after more than a year of constant rotation for ~12 hours each day, resulting in some loss in sensitivity which was restored by realignment of the tuning. Thereafter, this procedure became a routine yearly maintenance item. By late 1957, it was clear from the records of solar bursts that interesting spectral structure was being missed by the low frequency cutoff at 100 MHz in the records. Two more receivers, covering 25-50 MHz and 50-100 MHz, were obtained from A.I.L. These were mechanically tuned as in the 100-580 MHz receivers. The vacuum tubes for the tuned input stages were WE 417A triodes, which (unlike those for the 100-580 MHz receivers) were conventional tubes with electrode connections through base pins. For the 25-50 MHz receiver, the intermediate frequency (IF) stages included a crystal filter of width 40 kHz to contain the response to the strong interfering signals

encountered at these lower frequencies. The antennas for the new receivers were fixed bow-tie dipoles[4] in front of a plane reflecting screen with a fixed pointing direction toward the meridian at zero declination. The 25-50 MHz dipole was horizontally polarized and the 50-100 MHz one was orthogonal to it. These were able to pick up solar bursts over a wide range in hour angle. To accommodate the two new receivers, a new recording system with six cathode ray tubes and a camera using 70-mm film were obtained.[5]

The effective shielding of the site from FM, TV, and other signals in the 50-100 MHz range was demonstrated by the occurrence on the film records of occasional short bursts of interference as a result of reflections from meteor trails (Thompson 1961b). Typically about ten signals would be seen across the 50-100 MHz band, starting at approximately the same time, but with durations varying inversely as the square of the frequency. The overall duration of such a burst was usually a few seconds to two minutes. They were particularly noticeable during the Perseid meteor shower. In the same band there were also occasional periods of interference lasting for minutes to hours, attributable to reflection from sporadic-E in the ionosphere.

In 1959 a receiver covering 2100-3900 MHz was added which made use of the sixth cathode ray tube. When designing the 100-580 MHz feed system, Henry Jasik had first built a 1/6.82 scale model for test measurements, in which the 300-600 MHz horn of the full-scale feed was represented by a 2-4 GHz horn (Jasik 1958). As an extra benefit he added this small horn to the full-scale feed package, and it was brought into use from January 1960 to December 1961 with a new receiver obtained from A.I.L.[6] The input stage of this receiver was a Schottky diode mixer with a local oscillator using a backward-wave oscillator tube. Both sidebands from the mixer were accepted, and the IF response was 100 kHz to 5 MHz. The response to received signals was a band of width 10 MHz with a small gap in the center. This system was commonly referred to as a 'zero-IF' receiver because the center frequency of the received band was not offset from the local oscillator frequency. For further details see Thompson (1961a). In 1966, a receiver covering 10-25 MHz was added, for which a log-periodic antenna was obtained. This was pointed at a fixed elevation of 60° but could be adjusted in azimuth. Problems with observations in this low band are caused by ionospheric absorption and by the number of communication signals. Solar emissions were recorded, particularly during strong outbursts, but in general the 10-25 MHz band did not provide much useful data.

7 FURTHER EXPANSION OF THE SOLAR FREQUENCY RANGE

Because the site was substantially free from interfering signals at frequencies above a few tens of MHz, Maxwell realized that it would also be a good location for non-solar radio astronomy. An 85-ft. (25.9-m) diameter equatorially-mounted antenna was obtained in 1962 from the Blaw-Knox Co. of Pittsburg, PA, and the Harvard site at Cooke Flat was extended to 4 acres in order to accommodate the antenna and a new laboratory building, as shown in Figure 9.

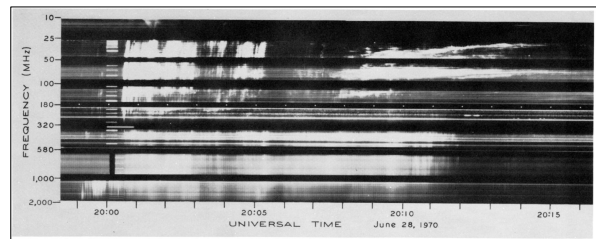Although it was not primarily intended for solar

Figure 7: A large radio outburst in which there is a group of Type III bursts between 20:00 and 20:05 UT and a Type II burst between 20:08 and 20:15 UT. The frequency coverage shown is 10 to 2000 MHz, and in the range from about 400 MHz to 2000 MHz there is strong Type IV continuum radiation (Figure supplied by A. Maxwell, Harvard College Observatory).

work, from March 1970 to March 1974 the 85-ft antenna was used for solar observations in the bands 580-1000 MHz, 1-2 GHz, and 2-4 GHz, as shown in Table 1. There were then as many as nine solar observing bands, so, when observations were made in more than six bands, the original three-band recording system with its 35-mm film camera was used in addition to the six-band system. During the period of solar observing with the 85-ft antenna, solar activity (as indicated by the sunspot numbers) was declining from the maximum of 1969 toward the minimum of 1976, as shown in Figure 8. No information has been found about the receivers used in these three bands covering 580 MHz to 4 GHz, but they were probably the 'zero-IF' type with a log-periodic feed. Solar bursts in these three highest frequency bands were mostly of the continuum Type IV classification, sometimes showing intensity pulsations with periods in the range 1-200 sec, as investigated by Maxwell and Fitzwilliam (1973).

Table 1: Frequency ranges and the corresponding antennas used in the solar program.

| Frequency Range	Antenna
10 – 25 MHz	Log-periodic, fixed elevation 60°, adjustable in azimuth.
25 – 50 MHz	Broadband dipole with plane reflector, fixed elevation 60°.
50 – 100 MHz	Broadband dipole with plane reflector, fixed elevation 60°.
100 – 180 MHz	28-ft. diameter tracking paraboloid.
180 – 320 MHz	28-ft. diameter tracking paraboloid.
320 – 480 MHz	28-ft. diameter tracking paraboloid.
580 – 1000 MHz	85-ft. diameter tracking paraboloid.
1000 – 2000 MHz	85-ft. diameter tracking paraboloid.
2000 – 4000 MHz	85-ft. diameter tracking paraboloid.
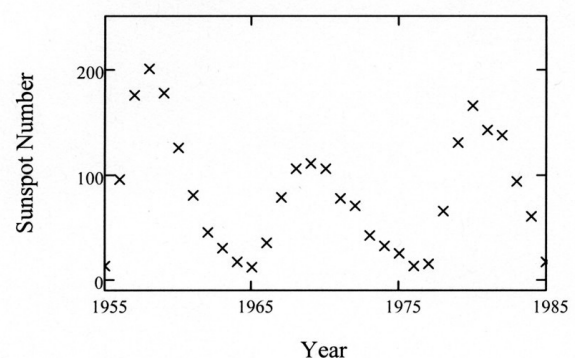
Figure 8: Yearly averages of the sunspot number. The Fort Davis observations spanned the years 1956-1982.

During 1977-1978 a new sweep-frequency receiver for the 50-100 MHz band, based on a commercial (Hewlett Packard) spectrum analyzer, was tested and found to perform well. In late 1979 and early 1980 all of the mechanically-tuned solar receivers were replaced with spectrum analyzer systems. Sensitivity with the new receivers was very similar to that with the old system, and an example of a record with the new system can be found in Maxwell et al. (1985).

From October 1956 to October 1982, the period in which solar observations were made at Fort Davis, there were sunspot maxima in 1958, 1969, and 1980 (see Figure 8). The years 1962-1966 and 1973-1977 were periods of low solar activity, and in some years as few as two Type II bursts were recorded. The frequency range 50-320 MHz was generally adequate to record events during such times. Thus the frequencies covered at any time depended upon the level of solar activity as well as the receivers available. Table 2 shows the frequency bands principally used at different times.

8 STATISTICS AND OPTICAL ASSOCIATIONS OF THE SOLAR BURSTS

In addition to providing data on all solar radio outbursts that occurred during daytime hours at Fort Davis, a number of studies of the statistics of the various types of bursts were made. These included the association with optical solar phenomena and geophysical events. Some of the more important results are summarized below.

Type I (noise storm) events, which persist for hours or days, generally occur when there is an active region on the Sun, but no statistically-significant association was found between their intensity and the occurrence of other types of radio outbursts or flares. Type II (slow drift) bursts often occur as part of a large outburst which starts as a group of strong Type III (fast drift) bursts and may be accompanied by continuum emission of Type IV or V. Such major radio events are usually associated with solar flares (Swarup et al., 1960; Maxwell and Thompson, 1962).[7] On the assumption that the emission occurs at the local plasma frequency, the radial velocity of the disturbances that produce Type II bursts was generally found to be within the range 700-1800 km/s, decreasing with frequency (i.e. with increasing coronal height). In relating the frequencies of bursts to the level in the solar corona, values used for the electron density (over active regions) as a function of height were ten times the quiet-Sun values given by the Baumbach-Allen or Saito models, and twice those of the Newkirk model, as explained by Dryer and Maxwell (1979). In the case of Type III (fast drift) bursts, about 50% were found to occur during times when a flare was present on the Sun, but examination of the statistics indicated that the number of such bursts causally associated with a flare was closer to 20%. Hughes and Harkness

Figure 9: The site in 1964. From left to right: the solar laboratory, the 28-ft. antenna, the 25-50 and 50-100 MHz dipoles and the 70 MHz monitoring antenna, the 85-ft. antenna, an extendable tower for access to the focus of the 85-ft. antenna, and the new laboratory building for the 85-ft. antenna. The figure near the 85-ft. antenna is laboratory assistant C. Murray (Photograph supplied by A. Maxwell, Harvard College Observatory).

(1963) examined the frequency variation with time in Type III bursts and estimated the radial component of velocity of the exciter of the plasma oscillations to be 40% of the speed of light. Both electron streams and electron plasma shock waves were discussed as the cause of Type III bursts, but subsequent analysis has eliminated the shock wave mechanism.

Bursts with continuum spectra (Types IV and V) are generally attributed to gyro-synchrotron radiation. Of these, the Type IV events often have durations of one or more hours and can extend to frequencies up to several GHz (Thompson, 1962; Thompson and Max-well, 1962; Maxwell et al., 1963). Most Type IV bursts recorded at Fort Davis were associated with large solar flares, 85% of which were within 60° of the solar meridian, indicating some restriction on the angle of emission of the radiation. Type V continuum bursts typically closely follow an intense group of Type III bursts. They were found to be strongest at frequencies below about 300 MHz. The duration increased with decreasing frequency and generally did not exceed a few minutes. Type V bursts were found to be associated with flares in more than 70% of cases. Detailed statistics of the various burst types can be found in the references given above. In general, associations of Type II and Type IV bursts with strong (class 3) flares were unambiguous, but with less energetic events the associations were often less clear.

In the periods 1972-1973 and 1979-1981, during or following sunspot maxima, large solar events recorded at Fort Davis resulted in a number of publications with respect to the generation of MHD shock-fronts by solar flares and their relation to Type II bursts (Max-well and Rinehart, 1974; Dryer and Maxwell, 1979; Maxwell and Dryer, 1982; Maxwell and Dryer, 1982-1983, Wu et al., 1983; Maxwell et al. 1985). These included theoretical studies of the propagation of fast-mode MHD shock waves in the solar plasma, and are one of the more important results of the solar program.

9 ASSOCIATION OF SOLAR BURSTS WITH GEOPHYSICAL PHENOMENA

Several papers were written on the association of bursts with geophysical events. The speed of disturb-ances associated with Type II bursts suggested an association with magnetic storms, i.e. the increases in the index of magnetic activity at the Earth often accompanied by auroral phenomena and Forbush de-creases in the cosmic ray count. These occur approxi-mately 30 hours after certain solar flares. An analysis of the Type II bursts that occurred during 1957-1958 resulted in the conclusion that bursts of this type are causally associated with the emission of auroral part-icle streams and associated phenomena (Maxwell, Thompson and Garmire, 1959; Thompson and Max-well, 1960b). Further investigation has indicated that the association is stronger when the Type II burst is accompanied by Type IV emission. Similarly, the speed of the disturbances associated with Type III bursts suggested that if the mechanism involves particle streams that are subsequently emitted from the Sun, these might be detected as variations in the cosmic ray flux at the Earth. However, analysis of the Fort Davis Type III data indicated no correlation with increases in the general cosmic ray level as recorded at the neutron monitor pile at Climax, Colorado (Thomp-

son, 1959a; Thompson and Maxwell, 1960b).

Another type of solar emission that is detected at the Earth is in the form of protons with energy of some tens of MeV, which at the time of the Fort Davis observations were sometimes referred to as low-energy cosmic rays. These cause increased ionospheric atten-uation of radio waves at high latitudes, resulting in conditions referred to as polar blackouts. The time delay between the solar outburst and the onset of the blackout is approximately 0.7 hr. The Fort Davis data showed a strong correlation between the occurrence of Type IV continuum emission and polar blackouts, especially in cases where the associated flare was in the western hemisphere of the Sun (Thompson and Maxwell, 1960a). This predominance of the western hemisphere in the related outburst positions suggests that the solar particles follow a curved path in space, guided by magnetic fields. For further discussion of the relationships between solar radio bursts, particular-ly Type II and Type IV, and the emission of solar protons with various energy ranges, see Maxwell (1963) and particularly Maxwell et al. (1964). Studies of how the radio emission is related to particle emis-sions and geophysical phenomena are among the most interesting and important results of the Fort Davis solar program.

Table 2: Time periods in the solar program and the corre-sponding frequency ranges observed.

Observing Period	Frequency Range
October 1956 – December 1958	100 – 580 MHz
January 1959 – December 1959	25 – 580 MHz
January 1960 – December 1961	25 – 580 MHz and 2.1 – 3.9 GHz
January 1962 – December 1962	25 – 580 MHz
January 1963 – March 1965	50 – 320 MHz
April 1965 – December 1966	25 – 320 MHz
January 1967 – February 1970	10 – 580 MHz
March 1970 – April 1970	10 – 1000 MHz
May 1970 – March 1973	10 – 2000 MHz
April 1973 – March 1974	10 – 4000 MHz
April 1974 – January 1978	25 – 320 MHz
February 1978 – October 1982	25 – 580 MHz

10 THE NON-SOLAR PROGRAM WITH THE 85-FT ANTENNA

Installation of the 85-ft antenna at the site was com-pleted by the end of 1962, and a new laboratory building was erected for the associated control and receiving equipment. The main purpose of the antenna was to allow an expansion of the astronomical pro-gram, particularly during periods of low solar activity.

Before leaving the project in December 1962, I built a simple receiver for first tests of the new antenna at a frequency of approximately 950 MHz. The receiver input was switched at 94 Hz between the antenna output and a 50-ohm load at ambient temperature, us-ing a switch (see Figure 10) with a design similar to one that Gordon Stanley had shown me at Caltech's Owens Valley Radio Observatory. The Fort Davis station had only minimal workshop facilities, so im-provization was sometimes necessary. Marlyn Krebs kindly provided the aluminum box parts for the switch, and I found some metal parts in the household plumb-ing supplies at the Fort Davis hardware store which I used for the transmission line and stub elements. The

switch isolation at 920, 950, and 980 MHz was 21, 31, and 19 dB, respectively. The input stage of the receiver was a 1N21F Schottky diode mixer, and the IF was 30 MHz with 5 MHz bandwidth. The IF input stage had a noise figure of approximately 0.7 dB using low-noise WE437A and WE417A vacuum tubes in a cascode circuit.[8] A gain modulator driven at the switching frequency allowed the signal levels with the two positions of the input switch to be balanced. The receiver was used for observations of lunar occultations at 950 MHz and appeared in several Fort Davis publications.
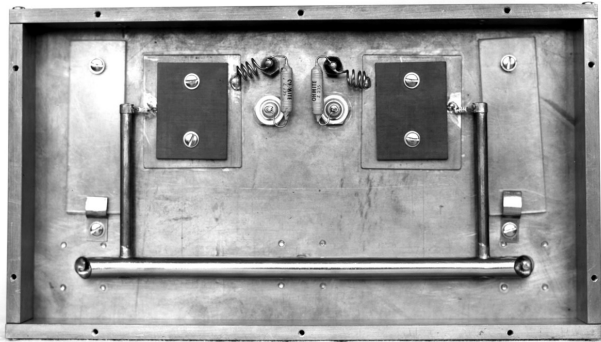

Figure 10: Input switch for a 950 MHz receiver made for initial observations with the 85-ft. antenna. The horizontal conductor in the lower part of the picture forms a 50-ohm line with respect to the mounting plate, which acts as a ground plane. A connector at one end of this line goes to the antenna and at the other end to a 50-ohm load. A connector at the center of the line goes to the receiver input. The two vertical stub lines are each a quarter wavelength long and are attached to the 50-ohm line at points a quarter wavelength from the central connector. (At radio wavelengths, a quarter wavelength of line effectively converts a short circuit into an open circuit, and vice versa.) The effective electrical lengths of the stubs can be adjusted by pieces of polystyrene sheet, the edges of which can be moved between the stubs and the ground plane. The top end of each stub is connected through a diode to a plate that forms a capacitor with the ground plane. Two square wave switching voltages, applied in opposite phase to these plates, cause the stubs to be alternatively open-circuit or capacitively shorted to ground. Thus the receiver input is alternately connected to the 50-ohm load or to the antenna. A switch designed on the same principles but using coaxial elements is described by Orhaug and Waltman (1962) (Photograph by the author).

In early 1963, a state-of-the-art receiver for 5 GHz with a parametric amplifier, obtained from A.I.L. (Hughes et al., 1965), was installed with a 5 GHz feed system from Jasik Labs. The input of this receiver was switched between the primary feed horn and a reference horn that could be pointed towards the antenna to produce a reference beam, or toward the cold sky at high elevation angles.

Publications show that the 85-ft antenna was being used regularly in non-solar projects by mid-1963. These included observations of occultations of sources by the Moon (Hughes, 1965; Taylor, 1966; Moffet et al., 1967; Maxwell and Taylor, 1968) and of the Crab Nebula by the Sun (Hughes et al., 1964). For most of the lunar occultations the data were recorded on paper tape and transferred to punched cards at Harvard for further analysis. Other programs included mapping of the Galactic Center (Maxwell and Downes, 1964), the Galactic Plane (Altenhoff et al., 1970), and star-forming regions, including Cygnus X (Downes and Rinehart, 1966). Measurements were made of flux

densities at 5 GHz for Galactic and extragalactic sources (Maxwell and Rinehart, 1966; Hughes, 1967), including planets (Hughes, 1966). Most of the published work with the 5 GHz receiver involved observations made before 1970.

In 1972, a U.S. program of very long baseline interferometry (VLBI) observations was initiated, in which the 85-ft antenna at Fort Davis was frequently used (Cohen et al., 1975). Other antennas included in these observations were the 30-m antenna at the Owens Valley Radio Observatory and the 40-m antenna of the NRAO in Green Bank. The Fort Davis location was particularly useful for VLBI since it provided intermediate baselines when combined with other radio astronomy antennas, many of which were located in the North-East or West-coastal regions of the U.S. After April 1974, the 85-ft antenna was used entirely for non-solar observations, mostly for VLBI. The VLBI program used frequencies 10.69 and 10.71 GHz, i.e. a wavelength of ~2.8 cm.

11 FURTHER DETAILS OF THE OBSERVATORY STAFF AND STUDENTS

Alan Maxwell lived principally in Fort Davis through the years 1956-1973 and then moved to Cambridge, MA. He continued to direct the solar operations which were carried out by technical staff at Fort Davis and included analysis of the film records. He retired in 1983. In addition to members of the research staff mentioned above, Daniel E. Harris was involved mainly with the non-solar activities during 1970-1973. Graduate students who completed work for Ph.D. theses at the station included Samuel J. Goldstein (Stanford Ph.D.), Joseph H. Taylor (as a Harvard graduate student, 1968-1969), Dennis Downes (as a Harvard undergraduate and graduate student 1964-1970), and David B. Shaffer (Caltech Ph.D.). Joe Taylor was later awarded the Nobel Prize for his work on relativistic effects of gravitation using timing of binary pulsars at the Arecibo Observatory. Other students from Harvard who worked at the station included Peter Stone, Stephen Cole, Gordon Garmire, William E. Howard III, Richard L. Harkness Jr., Richard J. Defouw, Larry Goad, Tom Wilson, Peter Cummings, Andrew Fraknoi, and Jim Fitzwilliam. Several other scientists spent time at Fort Davis as visitors. Figure 11 shows the 85-ft laboratory with some of the people mentioned above.

From 1976 to 1991, the VLBI programs were successively managed by John Ball, Paul Sebring, Jesse James, and J.D. Williams. Electronic technicians who worked at the station include Dino Parenti, Newell Sanford, Richard H. Ellis, and Paul Whitfield. Almost always one of the young people from Fort Davis, while a student at the high school or at Sul Ross State College in Alpine, had a job as laboratory assistant. Of these Ron F. Rinehart remained as a staff member through 1964-1975 and participated in observing programs.

12 CONCLUSION OF THE HARVARD SOLAR PROJECT

The solar observations continued until December 1982, after which the program was discontinued. All of the film records were sent to the National Oceanographic and Atmospheric Administration (NOAA) at

Boulder (CO) for archival storage. The VLBI program continued until October 1991,[9] when the NRAO's Very Long Baseline Array (VLBA) (Napier et al., 1994) took over with a new 25-m antenna at Cook Flat, specifically for that program. The VLBA antenna is located within a few hundred meters of the location of the original 85-ft antenna, which was demolished. The Fort Davis location thus remains an active radio astronomy site.

13 NOTES

1. At one point Sproul Road crosses the usually-dry bed of Limpia Creek. The creek sometimes flowed for a few hours after a thunderstorm in the mountains, and experience showed that at such times it was not always easy to judge whether the observatory pickup truck could make the crossing successfully!

2. The tripod feed-support structure on the 28-ft antenna was made of fiberglass, and was probably not designed for a feed as heavy as the 100-580 MHz structure. After about three years, cracks in the fiberglass were noticed near the centers of the feed support members. As on many occasions, Marlyn Krebs produced an answer to the problem. He improvised splints made from short lengths of oil-well casing, which provided the required support and remained in place on the antenna throughout its working lifetime.

3. CRPL (the Central Radio Propagation Laboratory) became part of ESSA, and later part of NOAA.

4. A photograph of the 25-100 MHz antennas in Thompson and Maxwell (1959) shows initial tests in which the dipoles were too close to the reflecting screen. Their positioning was subsequently re-adjusted. Broadband feeds for frequencies below 100 MHz would have been too large and too heavy to use on the 28-ft antenna.

5. This recording system was designed by Dr Richard Dunn, a scientist at the Sacramento Peak Solar Observatory.

6. The frequency range for this receiver was 2.1-3.9 GHz, i.e., just less than a factor of two to avoid second harmonic responses at the mixer input. The same receiver may have been used during 1973-1974 on the 85-ft antenna to cover the nominal band 2-4 GHz (see Table 2).

7. Note that the associations referred to here are based on the timing of the radio and optical outbursts since the Fort Davis radio telescopes did not measure positions of the solar bursts on the Sun.

8. A grounded-cathode triode followed by a grounded-grid triode.

9. During the period from 1982 until the ending of the Harvard program in 1991 the Fort Davis station was referred to as the Agassiz station for official Harvard purposes.

10. The list of references does not include those associated with the VLBI program, but otherwise is believed to be complete, or close thereto, for publications concerning the equipment and observations at the Fort Davis site. Not all of the listed references are mentioned in the text.

14 ACKNOWLEDGEMENTS

Figure 11: The 85-ft. antenna laboratory with control console and equipment racks. From front to rear the people are: Harvard undergraduate students L. Goad and T. Wilson, graduate students D. Downes and J.H. Taylor, and electronic technician N. Sanford (in the striped shirt) (Photograph supplied by A. Maxwell, Harvard College Observatory).

Many local people were most helpful and hospitable, especially in the early years of the project, particularly the Sproul, McIvor and Miller families. This was especially appreciated by those of us who had moved to Fort Davis shortly after arriving in the U.S., which included Maxwell, Swarup, Hughes and myself. Although the town of Fort Davis had no mayor, Mr. Barry Scobee, a Justice of the Peace, local historian, and newsman, essentially filled that position. He provided much advice and support for the Harvard staff. Marlyn Krebs of the McDonald Observatory was a great help on numerous occasions.

Finally, many thanks are due to Alan Maxwell, who provided Tables 1 and 2, photographs of the site and the records of solar bursts, information on students at the site and many other details. Figure 4 is reprinted here with the permission of Harvard University Press. Govind Swarup and Michael Hughes also provided invaluable help with recollections of the equipment and observations.

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